Fermi National Accelerator Laboratory

FERMILAB-Pub-81/35-EXP
8055.000

(Submitted to Nucl. Instrum. Methods)

A LITHIUM LENS FOR AXIALLY SYMMETRIC FOCUSING OF HIGH ENERGY PARTICLE BEAMS

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April 1981

Operated by Universities Research Association Inc. under contract with the Energy Research and Development Administration

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ABSTRACT

The Lithium lens for focusing 80 GeV proton beam onto a production target with a beam envelope function β=2 cm is considered. The lens has length 10 cm, diameter 0.5 cm, and focal length 55 cm at maximum magnetic field 140 kG. The basis for the choice of the main parameters is discussed. We describe the construction and performance of the lithium lens, its pulsed power supply system, and the air insulated matching transformer which is specially constructed to facilitate positioning and removal of the lens.

INTRODUCTION

Lithium cylinders carrying a large pulsed current have been used at the Institute of Nuclear Physics in Novosibirsk to focus electron and positron beams in the energy range from 120 to 430 MeV since 1975/1/. These focusing devices called lithium lenses, are in routine use to achieve high efficiency in positron production. Recent proposals for proton-antiproton colliding beam facilities/2,3,4/ have motivated the development of more powerful lenses for the analogous function of focusing high energy proton beam onto a small spot on the target and collecting a large fraction of the antiprotons diverging from it. This note treats in particular the design, construction, and operation of a lens for focusing an 80 GeV proton beam to a spot of ~0.1 mm radius. The general considerations entering into the fixing of aperture, maximum field, pulse repetition, etc. are discussed along with some important features of the pulsed current source, current transmission system, and lens mounting which are fundamental in an operational system.

In simplest terms the lens itself is a cylindrical lithium conductor excited by a unipolar current pulse. The version described in this report is 0.5 cm in diameter, 10 cm long, and is excited by a 60 μs pulse of ~160 kA on a 13 Hz operation cycle. Because the skin depth of lithium is about 2 mm for such pulses the current distribution is rather uniform except at the ends where conductor is connected to the current source. A uniform current distribution gives an azimuthal magnetic field within the conductor

$$B_\theta(r) = \frac{\mu I r}{2\pi r_o^2} \tag{1}$$

where r_o is the conductor radius, I is the current, and $\mu \approx \mu_o = 4\pi \times 10^{-7}$ (MKSA). Thus, there is a constant radial gradient of the field, and the lens, unlike a quadrupole, provides axially symmetric focusing. The optical properties and the peculiarities of construction of similar focusing systems have been considered in detail in references/5,6/.

Choice of the Basic Parameters

To obtain the most efficient production of antiprotons for cooling and injection into a storage ring it is necessary to focus the proton beam onto the target in a very small spot with, for example, radius r_B~0.1 mm. Parameters from a Fermilab beam cooling proposal/2/ are used in the following for concreteness.

To obtain the proton beam radius at a target equal to 0.1 mm for a given beam radial emittance value $\varepsilon = 5\cdot 10^{-7}$ m, the beam envelope function at the target determined as

$$\beta_o = \frac{r_B^2}{\varepsilon} \tag{2}$$

has to be equal to 0.02 m. In this case the beam convergence angle is

$$\alpha_c = \sqrt{\varepsilon/\beta_o} = 5\cdot 10^{-3} \ . \tag{3}$$

Therefore, the maximum field integral along an extreme trajectory of a particle passing through a lens of length ℓ, which provides the necessary deflection angle, must be

$$\mathrm{Max}\left\{\int B d\ell\right\} = B_{max}\,\ell = \alpha_c\,\beta\rho \qquad (4)$$

where $\beta\rho$ is the magnetic rigidity of the beam; for 80 GeV/c, $B_{max}\ell = 13.3$ kG·m. The length of the lens is limited by the acceptable beam loss from nuclear interactions in the lens. The nuclear collision length for lithium is about 1 m so that the choice ℓ=10 cm results in a beam loss ~10%.

The field B_{max} on the outer surface of the conductor may be reasonably taken as 130 kG as shown in reference 6. From this point of view, one fixes β_o by the choice of B_{max} and ℓ and can choose either the focal length or the aperture as a free parameter. The aperture r_o and focal length F are now related by

$$r_o = F\cdot\alpha_c. \qquad (5)$$

One restriction on r_o comes from multiple scattering. Because the angle of multiple scattering θ_{ms} adds in quadrature to the angular spread in the beam,

$$\alpha_B = \frac{\varepsilon}{r_o} \qquad (6)$$

it is adequate to limit it to somewhat less than one half the angular spread in the beam evaluated at the principal plane of the lens,

$$r_o < \tfrac{1}{2}\,\frac{\varepsilon}{\theta_{ms}} \qquad (7)$$

The multiple scattering of 80 GeV protons in 10 cm of lithium is $\sqrt{\langle\theta^2_{ms}\rangle} = 6\times10^{-5}$. Thus, from eqn. 7 r_o must be less than 4.2 mm and correspondingly F must be less the 0.8 m by eqn. 5. The lens with chosen parameters ℓ = 10 cm, r_o = 0.25 cm, B_{max} = 130 kG has focal length

$$F = (\sqrt{K} \sin \sqrt{K}\, \ell)^{-1} = 54 \text{ cm} \tag{8}$$

where $K = \frac{1}{\beta\rho} \frac{dB}{dr}$. Such a lens satisfies all the criteria introduced above.

From a technical standpoint the minimum r_o compatible with the basic requirements is desirable because it requires the least excitation current. The lower the current, the less demand on current contacts, the less resistive heating, and the less field energy. For all of these reasons the smaller the radius is, the simpler are the mechanical requirements. It cannot be made arbitrarily small, however, because there is a relation between r_o and the skin depth δ which results from reconciling the conflict between the need for uniform current distribution (δ/r_o large) and the need to limit resistive heating (δ/r_o small). For $\delta/r_o = 0.7$ the current distribution is uniform to 0.5%/5/. With this ratio fixed one must reduce the pulse length when reducing the radius since

$$\delta = \sqrt{\frac{2\rho\tau}{\pi\mu_o}} \tag{9}$$

where $\rho = 10^{-7}\ \Omega\text{m}$ for lithium and τ = the pulse width. The minimum pulse width is subject to the technical consideration that the required high voltage varies inversely as r_o and a fundamental requirement for good regulation while the beam is passing through the lens. Because the variation in convergence angle during the beam pulse adds to the angular spread in the beam, the pulse length is chosen to keep this addition to a small fraction of the intrinsic angular spread α_B. For the Fermilab proton beam one has a beam spill of 1.6 μs and $\alpha_B = 2\times10^{-4}$ from eqn. 6. Taking the convergence angle α_c from eqn. 3 leads to a regulation requirement of $\pm5\times10^{-3}$ to avoid adding more than 10% to the beam spread. A pulse of 25 μs width already meets this requirement compared to the 60 μs minimum set by the skin depth at $r_o = 0.25$ cm; pulse width would have importance for field stability only for a substantially longer beam spill.

Design and Fabrication

Figure 1 shows the lithium lens installed directly on the secondary of the pulse transformer which drives it. This transformer, the motor driven positioning frame also appearing in the figure, and the required pulsed power source and transmission system are described later. Both the design parameters and measured properties of the lens are summarized in the Table.

Despite the simplicity of the concept, the lithium lens is complicated in reality because of mechanical requirements arising from stresses produced by the magnetic field and pulsed heating, the need for a uniform current feed of low inductance and low resistance, the need for water cooling, the chemical activity of lithium, and the need for radiation resistance. To satisfy all of these requirements simultaneously has required care in the choice of materials and fabrication techniques. Operation of cylindrical lenses with magnetic fields of 100 kG and higher is accompanied by strong heating of the lithium; the change in temperature during a pulse is $\Delta T_p \geq 76^{o}C$ at 100 kG and is proportional to B^2_{max}. Thus, the mechanical structure must not only withstand the stress caused by the pressure of the magnetic field but also that arising from thermal expansion of lithium. Lithium has a large coefficient of volume expansion, $\eta = 1.8\times10^{-4}$, and a 1.5% volume increase during melting. To simplify construction it is expedient to adopt an operational mode in which the lithium does not melt. In this case the cooling system must insure that the average temperature of the central lithium is limited to $T_{av} \leq T_m - \Delta T_p$ where $T_m = 186^{o}C$ is the lithium fusion temperature. This limit becomes a dominant concern in designing a lens for multi-Hertz operation. The version of the lens detailed below is strongly influenced by the need for fast cooling to sustain a 13 Hz cycle. A simple modification intended for .5 Hz operation has been run at 180 kG.

The functional part of the lens (see Figure 2) is the thin walled titanium cylinder (1) filled with lithium (2). The outside of this cylinder is in contact with water (3). The titanium cylinder is the most important element of the construction, determining the durability of the lens, and it must satisfy conflicting requirements. Because the equilibrium current flow is distributed between the titanium and the lithium in inverse proportion to their respective resistances, the cylinder wall should be thin to make $I_{Ti}/I_{Li} = (\rho_{Li}/S_{Li})/(\rho_{Ti}/S_{Ti}) < 0.1$. The cylinder is made from high-Om titanium alloy BT-6 for which the resistivity $\rho_{Ti} = 1.6\times10^{-6}\ \Omega$ whereas $\rho_{Li} = 10^{-7}\ \Omega m$; thus, for this lens with $r_o = 2.5$ mm and cylinder wall of thickness $\Delta = 0.7$ mm, $I_{Ti}/I_{Li} = 0.04$. Titanium alloys have low thermal conductivity, $\lambda_{Ti} = 0.018\ \mathrm{cal\cdot cm^{-1}s^{-1}{}^{o}C^{-1}}$. For this reason also the cylinder wall must be thin to reduce the temperature drop $\Delta T_\lambda \propto \Delta$ across the wall. On the contrary, however, the wall should be thick to withstand the load caused by the magnetic field and the expansion of the lithium during the pulse. The pressure produced by the magnetic field by uniform current distribution is

$$p(r) = p_o\ (1 - \frac{r^2}{r_o^2}), \quad p_o = \frac{B_{max}^2}{8\pi}\ ; \tag{10}$$

$p_o = 400\ \mathrm{kg/cm^2}$ at 100 kG. Because the lithium is in a closed container the inner (1) and outer (4) titanium cylinders are the structural elements which are deformed by the volume expansion of lithium. It is assumed that under a few hundred atmospheres pressure lithium behaves like a liquid. The wall thicknesses are chosen such that for pressure not greater than 1000 atm, the deformation will not exceed the elastic limit and the stresses do not exceed $\delta \approx 3500\ \mathrm{kg/cm^2}$ permissible for titanium alloys. At the ends of the inner cylinder the walls are smoothly thickened and flared to avoid the concentration of stresses caused by the force moment appearing at the joining of the inner and outer cylinders which are welded over their outer perimeter (6) to increase the welding area. Two methods of welding have been tested: electron beam vacuum welding and electric arc welding in an argon atmosphere. The latter is the simpler way and gives satisfactory results. To remove stresses after welding the entire internal titanium part together with the BeO ceramic insulators (11,12) is annealed in vacuum at 900°C. A water circuit (3,9) providing uniform water flow between the titanium cylinders (1,4) is formed by placing additional separating cylinders (8) and an internal ceramic insert (12) between them. These additional cylinders and ceramic are cut in half lengthwise so that they can be placed over the internal cylinder before it is welded to the outer. The ceramic ring (11) is the insulator which separates the current feed and return contacts. To seal the joint between the ceramic and the titanium, a heat softened copper foil is used which is compressed to yield by a special tool before the welds are made. The current feed to the operating part of the lens is through the peripheral lithium (5) which is contained by steel sleeves (7,14). The outside of these sleeves are the current contacts which are tightly clamped to the secondary turn of the driving transformer. At each end of the lens assembly is an oxide coated titanium end cap (19) with a beryllium beam window (15). The endcap is insulated electrically from the current contacts by a BeO ceramic ring (20) which is protected against cracking by the thin lead washers (21) on either side of it. The window and ceramic insulators are fit into a titanium flange (18). The inside surface of the window and the flange are covered by a titanium foil (16) to seal the joint between them. The seal between the current contact (7) and the end cap assembly and likewise between the current contact and the flange of the outer titanium cylinder is provided by the narrow lead washers (13,17). The structure is united by six longitudinal titanium rods (10) threaded at the ends for nuts. The rods carry no current because the end cap are oxide coated and the rods are wrapped with polyamide film or likewise oxide coated.

The process by which this structure is filled with lithium has been described elsewhere/7/. The general technique is to flush the lens with inert gas and then fill it with molten lithium under a pressure of ~200 kg/cm^2. When the lens is full the temperature is reduced while the pressure is increased going to ~700 kg/cm^2 when the temperature has dropped below 100^{o}C. Voids or weak spots in the lithium are prevented by maintaining a considerable temperature gradient toward the axis of the lens so that the lithium is always subject to a strong constraining force.

Thermal Conditions

It has been mentioned that the dominant problem for multi-Hertz operation is to dissipate the heat liberated in the functional part of the lens. For a lens of 0.5 cm diameter the heat released in the lithium during one pulse at 100 kG amounts to $Q_p \approx 7$ cal for each centimeter of length or 35 cal/cm^3. This heat is carried away by the water through the thin wall of the inner titanium cylinder (see Figure 2), and the temperature drop on the titanium may be evaluated as

$$\Delta T_\lambda = \frac{Q_p \Delta}{\lambda \tau_i 2\pi (r_o + \Delta/2)} . \tag{11}$$

At 10 Hz operating frequency (τ_i=0.1s) and wall thickness Δ=0.7 mm the temperature drop is ΔT_λ=150^{o}C, and the power dissipated from the cylinder surface is 140 W/cm^2. The gap between the inner cylinder (1) and the separating cylinders (8) through which the water flows is 0.5 mm so that if the water flow is ~5 l/min its velocity is about 6 m/s and the temperature drop between the water and the titanium can be ΔT_W ~ 20^{o}C. Hence, the mean temperature of the lithium in this mode is

$$T_{av} = \Delta T_{\lambda} + \Delta T_{W} + T_{o} \approx 180^{o}C \tag{12}$$

However, this does not mean that the pulsed heating will lead to melting the lithium since the heat of fusion for lithium (Q_F=83 cal/cm^3) is higher than the heat liberated per pulse (35 cal/cm^3). Note that melting of the lithium is not a limiation in principle because it leads only to increasing the mechanical stresses in the structure resulting from the sharp additional expansion during melting. In reference (6) several structures are described and experimental results are presented aimed at obtaining magnetic fields up to 300 kG on lithium cylinders. With such a field the pulsed heating of the lithium is $\Delta T_p \approx 800^{o}C$. This figure is an estimate intended only for guiding design. The tests performed on the lens described in this paper show that in the limiting mode of 13 Hz continuous operation at 100 kG the average temperature of the lithium was T_{av}=170^{o}C as measured by a thermocouple located in the center of the lens.

Mounting and Current Source

The lens must be coupled to a pulsed current source with very low inductance and resistance. This requirement is met by a sequence of pulse transformers which match a more manageable current source to a transmission system and then to the lens. The lens is mounted directly to the single-turn secondary of the last transformer of this seuqence by mating fittings machined from the same block of aluminum from which the secondary itself is machined. This transformer, visible in Figure 1 is about 30 cm long by 14 cm wide by 21 cm high. The six turn primary is also machined from an aluminum block. The laminated core is enclosed in a stainless steel case. The secondary can be removed easily because the core is not continued through the center of the turns. The center of each primary turn, however, is filled with iron. This feature allows easy remote alignment or easy removal of a lens assembly from a high radiation area. Because the core has a total gap of about 5 × 10 mm, the transformer has only about 60% efficiency for 125 kA (100 kG) operation. It is not difficult to make a more efficient transformer by using a complete core, but the convenience of having the secondary freely moveable does not cost unduly for this relatively low energy system.

A mounting frame designed to carry two complete lens and transformer secondary assemblies is mounted to the transformer frame. The secondary is held rigidly and precisely in place on the frame by being fit over two tapered locating pins. It is locked down by wedges mounted on the secondary top plate which are forced horizontally through keyways in the positioning pins by a cam actuator. The water supply and return connections for the lens are tied firmly to the transformer case but include bellows to follow the travel of the mounting frame. To permit easy removal of the secondary, the lens water system is connected between the secondary and the transformer case by spring loaded compression fittings with lead washers between beveled nipples which can be separated freely when the locking wedges are withdrawn from the positioning pins. A horizontal screw drive is used either for alignment or to substitute one lens and secondary combination for another in the beam. A vertical drive is included to make small movements for alignment. The small dc motors powering these drives which appear in Figure 1 are not radiation resistant and must be replaced by air turbines, for example, for installation in a high radiation area.

The pulsed current source consists of a 100 μF low inductance energy storage capacitor discharged through the primary of a voltage step up (1:4 turns ratio) impulse transformer by a thyristor switch. The secondary can connect to 50 meters of parallel coaxial cable to separate the power supply from the beam area.

A second current step-up transformer (6:1 turns ratio) is connected by up to 6 m of very low inductance strip line or air insulated coaxial line to the (6:1) transformer on which the lens is mounted. To hold the contribution of the stray inductance of the transmission system to load impedance at the power supply to less than 10% of that presented by the lens, one must keep the inductance in the primary circuit of the 1:4 transformer to less than $1.5 \cdot 10^{-7}$ H. Of order $2 \cdot 10^{-6}$ H inductance is permissable in the cables up to the first 6:1 transformer and about $5 \cdot 10^{-8}$ H between this transformer and the final one. The supply should be provided with a crowbar or energy recovery circuit so that there is no reverse current through the lens to produce unnecessary heat.

Operation

Several samples of this version of the lithium lens have been made and tested. One was used for a life test of $>10^7$ pulses at 100 kG on a 13 Hz cycle. This lens was unharmed at the end of the test and was then used to check the maximum field sustainable in operation on a slower cycle. The lens was operated on a 0.5 Hz cycle at 124, 155, 181 and 205 kA (100-164 kG). About 2000 pulses were taken for each step but the last; the lens failed after about 20 pulses at 205 kA. At 181 kA (145 kG) the lens survived at least for the short term.

The failure mode in this case was a crack like rupture ~2 cm long near the middle of the inner titanium cylinder. In the course of developing this lens such cracks had generally been observed as the result of excessive average temperature rather than as the effect of single pulse stress. High field failures generally occurred at the weld joining the inner and outer cylinders. The low repetition rate of this test, however, ensures that the average temperature was modest; apparently the efforts to develop strong welds have succeeded sufficiently that they are no longer necessarily the weak spot in the structure.

If the high repetition rate is not needed there is no difficulty in obtaining substantially higher field in the same basic design. A very similar lens differing only in the thickness of the wall of the inner cylinder being 1 mm instead of 0.7 mm was made for tests at 0.5 Hz. This lens sustained about 4000 pulses at 184 kG before being raised to 200 kG. At this field the lens failed, again with an inner tube broken near the center. In this latter case the tube was broken straight across. The results of these tests and the operating temperature measurements described earlier agree rather well with the calculated stresses and the published properties of the materials. The challenge in making these lenses or those for some different application is primarily to construct an adequate scheme for mechanical containment and cooling of the lithium.

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Table I

Design Parameters and
Measured Properties of Lithium Lens

Maximum Field, B_{max}	100 kG
Length, ℓ	10 cm
Radius, r_o	2.5 mm
Maximum Current, I	130 kA
Current Pulse Width, τ	60 μs
Repetition Rate	13 Hz
Inductance, L	5×10^{-8} H
Resistance, R	$\sim7\times10^{-4}$ Ω
Thickness inner Ti wall, Δ	0.7 mm
Temperature drop across Ti wall, ΔT_λ	150°C
Average operating temperature	170°C
Cooling water capacity	4 ml
Cooling water flow	~5 l/min
Water pressure differential	~4 atm
Maximum water pressure, static	12 atm
Temperature drop between Ti and water	~20°C
Service Life	$>10^7$
Maximum Field at 5 Hz	120 kG
Maximum Field sustainable (.5 Hz oper)	145 kG